Development of the design method for the optimal design of the Neutron Converter experimental plant

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The article discusses methods for optimizing the design of the Neutron Converter research plant design with parameters that are most suitable for a particular consumer. 38 similar plant structures with different materials and sources were calculated, on the basis of which the most optimal options were found. As part of the interaction between OKBM Afrikantov JSC and the Nizhny Novgorod State Technical University named after R. E. Alekseev, the Neutron Converter research plant was designed and assembled. The universal neutron converter is a device for converting a stream of fast neutrons emitted by isotopic sources into a "standardized" value of flux density with known parameters in the volume of the central part of the product, which is the working part of the universal neutron converter. To supply neutron converters to other customer organizations (universities, research organizations and collective centers), it is necessary to take into account the experience of operating an existing facility, as well as rationalize the design process of each specific instance in accordance with the requirements of the customer.

Keywords: *neutron converter, sources of ionizing radiation, gamma radiation, neutron radiation, biological protection, neutron deceleration.*

1. Introduction

The scheme and method of arrangement of isotopic neutron sources selected in the project provide the maximum possible uniformity (isotropy and uniformity of axial-radial distribution) of thermal neutron flux density in the scope of the working part of the universal neutron converter [1].

The goal is to develop a universal design method for the optimal design of the Neutron Converter experimental plant to select the most suitable version of the plant for a particular consumer. In order to achieve this goal, it is necessary to perform the following tasks: to study the normative documentation on the use of ionizing radiation sources; examine the design of the existing experimental plant and construct and calculate the model of the existing design model; develop a methodology for finding the most suitable plant parameters for a particular consumer; calculate neutron fluxes and radiation doses at various versions of the experimental installation; analyze the results of the calculations.

2. Regulatory documentation

Neutron sources are required for neutron converter operation. Therefore, documents regulating ionizing radiation sources operation were reviewed. The main documents are: Federal Law No. 170-FL "On the Use of Atomic Energy" [2], Radiation Safety Standards (NRB-99/2009) [3] and Basic Sanitary Rules for Ensuring Radiation Safety (OSPORB-99/2010) [4].

The above regulations postulate.

1: During the design and installation of the converter, measures must be taken to ensure biological protection that meets the above requirements. Biological protection shall ensure that doses and dose capacities established for radioactive material handling are not exceeded.

2. Persons involved in the work of the converter: employees and students of the department - must be considered personnel of group B, and all other persons - the population. This separation should be taken into account when allowing specialists to work with the plant and in the room where it is located.

3. The operating organization (department "Nuclear reactors and power plants" of the Institute of Nuclear Energy and Technical Physics named after Academician F.M. Mitenkov) should develop regulations for the operation of the plant, the procedure for admission to it, as well as organize its maintenance and radiation control.

Based on these documents, conclusions were drawn about the necessary degree of protection during the operation of the plant.

It was calculated that in order to comply with the standards for dose limits received by personnel when working with a neutron converter, the biological protection of the plant should provide a total equivalent dose rate of neutron and gamma radiation at a distance of 10 cm from the hull of not more than 1.15 mSv/h. This value is the determining value when designing the biological protection of the converter.

3. Analyze the design of an existing plant

The universal neutron converter is a device for converting a stream of fast neutrons emitted by isotopic sources into a stream of thermal neutrons in the volume of the central part of the product (Fig. 1).

To convert the fast neutron flux, it is necessary to reduce their energy by "converting" them to thermal ones. This process occurs due to the deceleration of neutrons during scattering of the moderator elements on the nuclei. The periphery of the universal neutron converter performs the functions of biological protection.

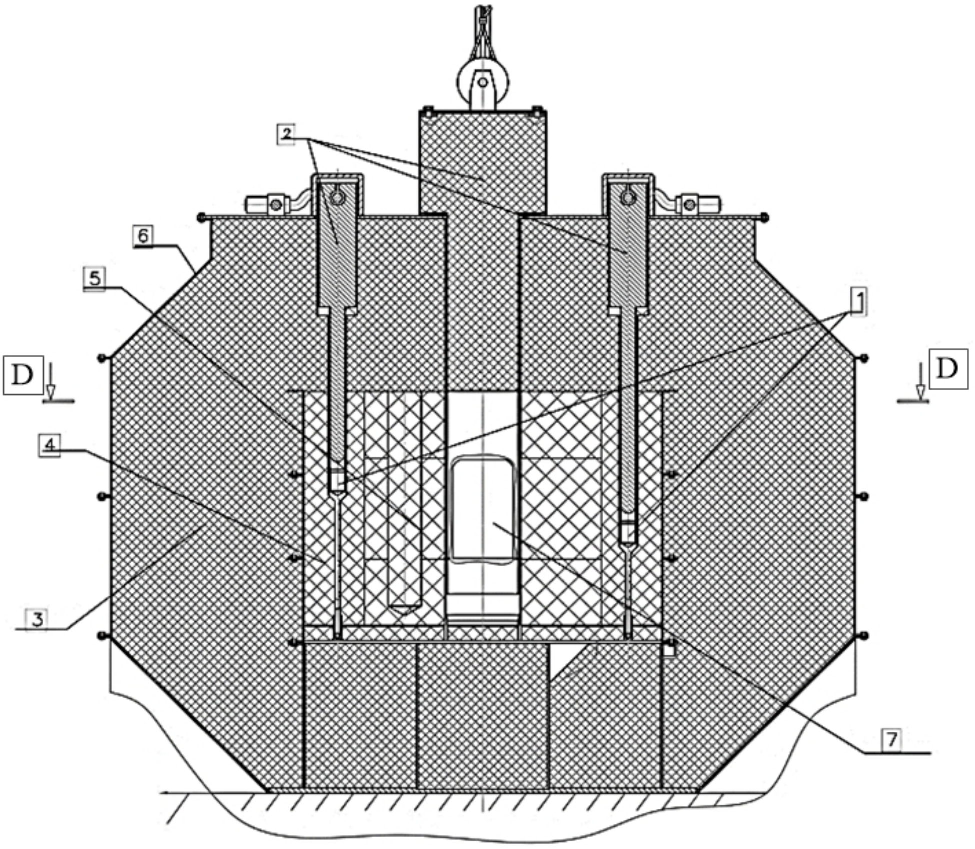

Fig. 1. Design diagram of neutron converter: 1- neutron sources, 2 - plugs, 3 - biological protection, 4 - paraffin, 5-graphite, 6 - housing, 7 - working cavity

The advantages and disadvantages of the design of the existing plant were analyzed. Both used and potentially suitable as retardant and/or biological protection of the converter structural materials were considered during the analysis. It was concluded that it is possible to create a variant of the installation design that provides the required parameters of neutron radiation, but with smaller weights or overall dimensions than the existing version of the converter design.

As neutron sources in the plant, various plutonium-beryllium (fast neutron sources (FNS) - FNS-6, FNS-8) and Californium sources were considered, their radiation spectra necessary for further calculations in programs were identified and digitized.

For the design of this type of installations, the dose capacities outside the existing installation and the density of the thermal neutron flux in its working cavity were calculated using DOT III programs, and DotGeom designed to automate the entry of the DOT program setting zones (Fig. 2) [4].

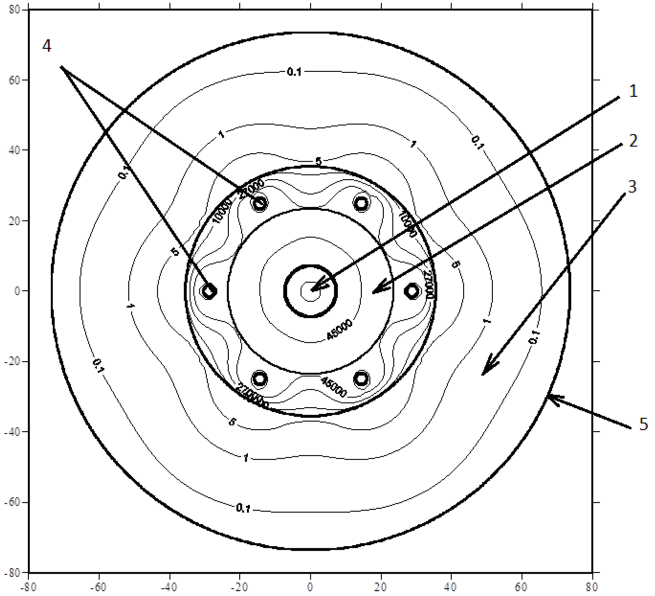

Fig. 2. Thermal neutron flux distribution in existing plant, n/(cm^2·s): 1-working cavity, 2- retarder layers, 3-biological protection layers, 4-sources, 5-housing

Dose capacities outside the existing plant, and the density of the flux of thermal neutrons in its working cavity were calculated.

4. Technique of optimizing converter design procedure

To create an optimal neutron converter design procedure, a basic set of 38 versions of the plant was compiled and calculated, differing in the neutron sources and moderator and protection materials used. In each of these embodiments, the best combination of input and output characteristics is found. After analyzing and comparing the optimal implementations of each of the 38 variants, it was concluded that the most preferred embodiment was the best structural materials and neutron sources for use in the plant.

Since the efficiency of the combined protection differs from the monolithic one, combinations of two materials were selected as the initial data. All design versions of neutron converter are given in Table 1.

Table 1. Versions of neutron converter

Ver.	Source type	First Material	Second Material
1	Californium	Paraffin	Graphite
2	Californium	Graphite	Water
3	Californium	Loose mix	
4	Californium	Polyethylene	Graphite
5	Californium	Polyethylene	Paraffin
6	Californium	Titanium hydride	Polyethylene
7	Californium	Paraffin	Titanium hydride
8	Californium	Concrete	
9	Californium	Graphite	Vaseline
10	Californium	Graphite	Concrete
11	Californium	Water	Lead
12	Californium	Polyethylene	Lead
13	FNS-6	Concrete	Graphite
14	FNS-6	Titanium hydride	
15	FNS-6	Graphite	Titanium hydride
16	FNS-6	Concrete	Polyethylene
17	FNS-6	Graphite	Paraffin
18	FNS-6	Paraffin	
19	FNS-6	Concrete	Water
20	FNS-6	Paraffin	Lead
21	FNS-6	Graphite	Polyethylene
22	FNS-6	Vaseline	Graphite
23	FNS-6	Water	Graphite
24	FNS-6	Loose mix	Graphite
25	FNS-6	Vaseline	Polyethylene
26	FNS-8	Concrete	Graphite
27	FNS-8	Titanium hydride	
28	FNS-8	Graphite	Titanium hydride
29	FNS-8	Concrete	Polyethylene
30	FNS-8	Graphite	Paraffin
31	FNS-8	Paraffin	
32	FNS-8	Concrete	Water
33	FNS-8	Paraffin	Lead
34	FNS-8	Graphite	Polyethylene
35	FNS-8	Vaseline	Graphite
36	FNS-8	Water	Graphite
37	FNS-8	Loose mix	Graphite
38	FNS-8	Vaseline	Polyethylene

The calculation of each version of the neutron converter design consisted of 2 stages: the calculation of the moderator and the calculation of biological protection. The task of the first stage of neutron converter design is to select and calculate moderator thicknesses, which provide the maximum possible, when using these materials, flux of thermal neutrons in the working cavity of the plant. When choosing the thickness of the layers, the main criterion was the flux of thermal neutrons in the working area. Criteria such as weight and size parameters and cost were secondary, since most of the cost, weight and size of the plant provides biological protection (Fig. 3, 4).

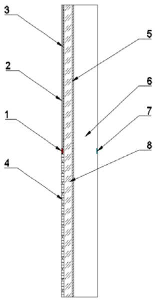

Fig. 3. Moderators in vertical section of converter: 1- source; 2- air in the source channel; 3- source sleeve; 4- first layer of moderator; 5 - shell of the central channel; 6- air in the central channel of the converter; 7- the cell in which the object to be irradiated will be located; 8-second layer of moderator

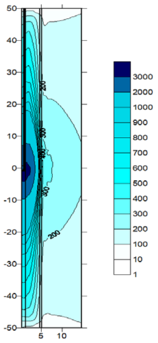

Fig. 4. Example of neutron flux density distribution in one of design variants

The second stage is the calculation of biological protection. The main task of designing the biological protection of the neutron converter is to select and calculate the necessary thicknesses of biological protection materials that provide the maximum permissible dose rate level at a distance of 10 cm from the column body with the minimum possible values of their weight and size parameters.

To do this, a calculation was made in R-Z geometry, which is part of the vertical section of the column in the direction from the source to the surface of the column (Fig. 5, 6).

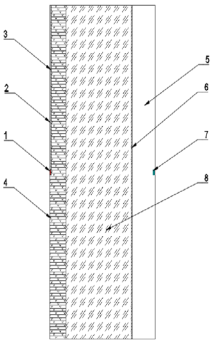

Fig. 5. Biological protection in vertical section of converter: 1- source; 2- air in the source channel; 3- source sleeve; 4- the first layer of biological protection; 5- space around converter; 6- converter housing; 7- neutron and gamma radiation dose rate calculation cell; 8 - second layer of biological protection

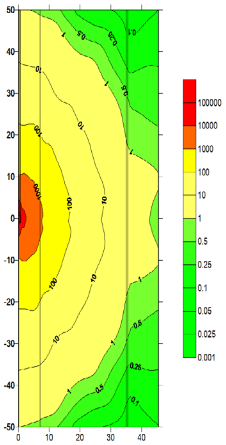

Fig. 6. Example of calculation results of neutron radiation dose rate distribution for one of design options

All versions of the column were divided into 3 groups of three types of sources: Californium, FNS-6 and FNS-8 (Figs 7-9).

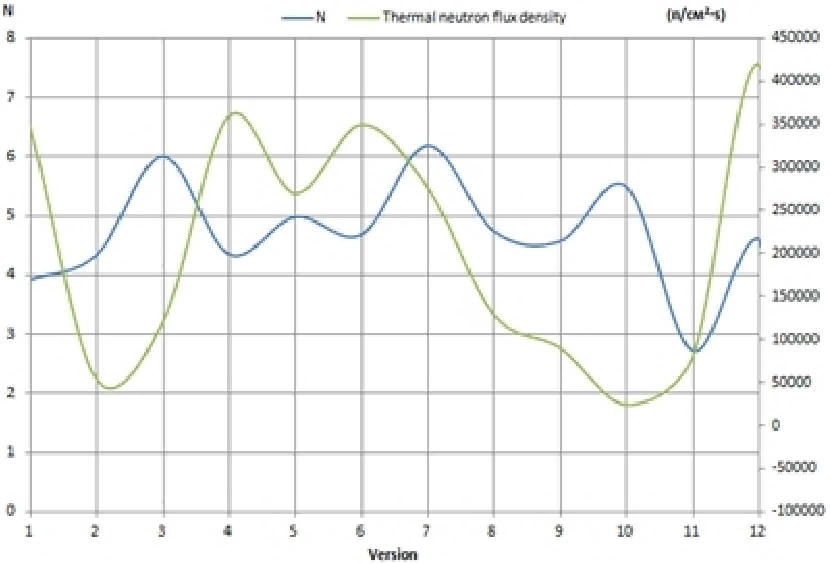

Fig. 7. Generalized coefficient N and flux density of thermal neutrons in the working area of the converter in Californium source design embodiments

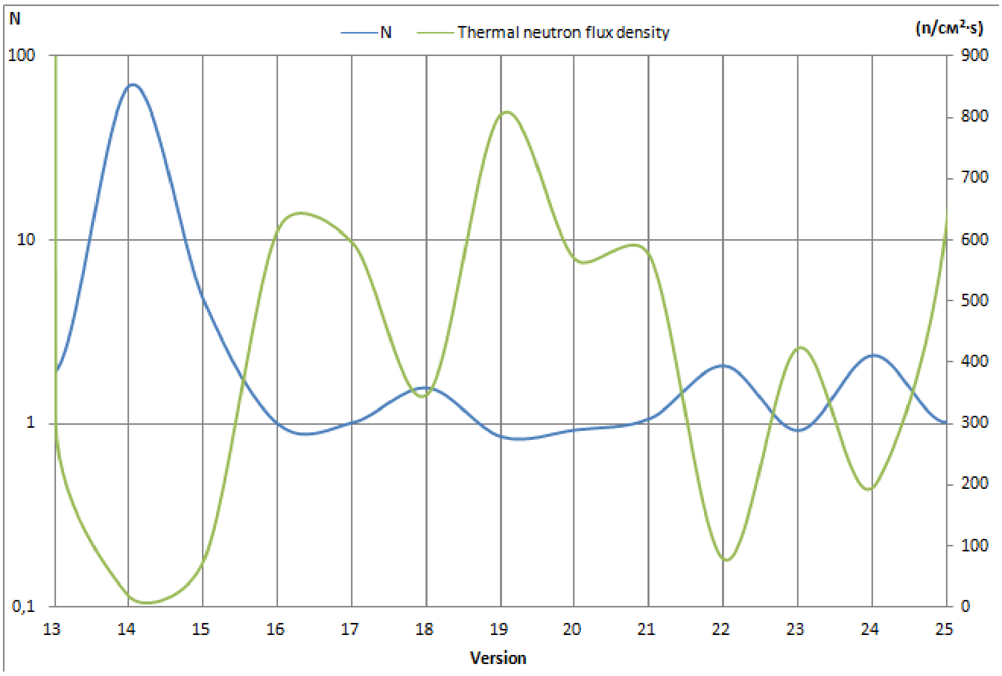

Fig. 8. Generalized coefficient N and flux density of thermal neutrons in working area of converter in versions with source FNS-6

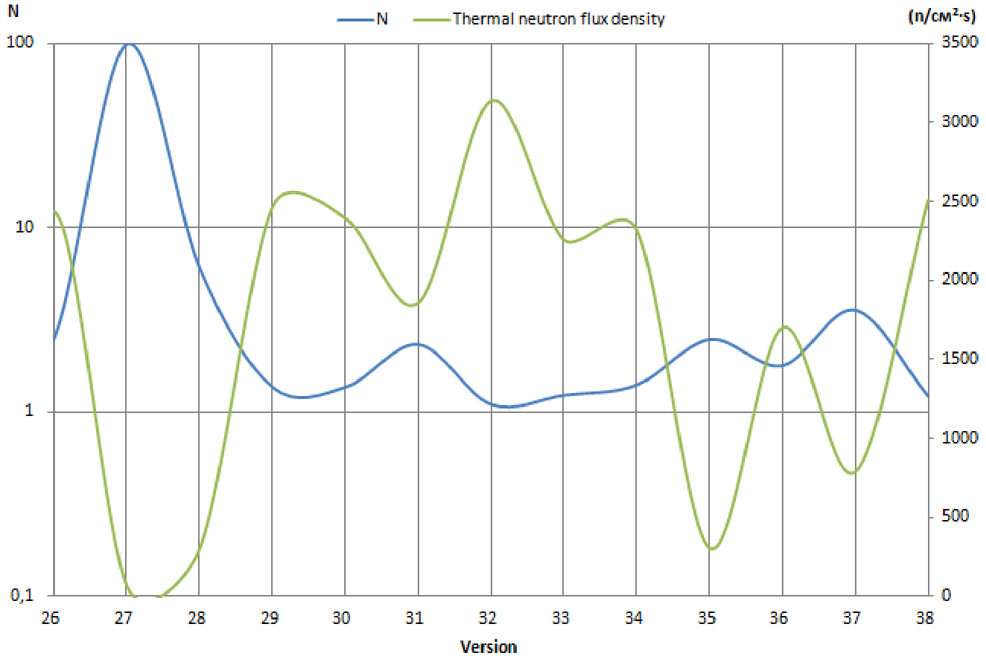

Fig. 9. Generalized coefficient N and flux density of thermal neutrons in working area of converter in versions with source FNS-8

All converter characteristics during design can be divided into 2 groups: input and output. Input characteristics are: source type, biological protection materials (BP) and retardant. The output characteristics are: the thickness and materials of the layers necessary to obtain the highest density of the thermal neutron flux while observing radiation safety standards, the density of the thermal neutron flux in the working cavity of the plant, mass and size and cost parameters of the converter [5-8].

In order to obtain the most efficient installation, it is necessary to strive to increase the parameter of the thermal neutron flux in the center and to reduce the values of mass, size, cost.

Each embodiment of the neutron converter has 4 defining characteristics. When comparing different options, it becomes necessary to analyze a 4-dimensional system of parameters, which is quite difficult without using additional tools. Therefore, in the process of optimizing the design procedure, it is necessary to bring some parameters to relative values and then convolve them as part of a complex criterion in order to reduce their number. The parameters of the mass, size and cost of the column materials were led to relative values, which, in turn, were reduced to one value - a comprehensive indicator of the quality of the design procedure - generalized coefficient N. The result of using this procedure is to reduce the number of output characteristics in the considered versions to two, as a result of which analysis and comparison of the calculated versions of the neutron converter design is carried out according to the value of heat flux in the working zone with a minimum coefficient N, which determines weight and size and cost characteristics.

5. Calculation results

38 versions of neutron converter design were analyzed and 3 versions were defined, one for each type of source, having an optimal set of parameters: maximum flux of thermal neutrons in the working area of the plant with minimum weight and size parameters and cost.

Among the options using the Californium source, the best way was to achieve the maximum density of thermal neutron flux in the working zone of the plant, equal to 4.2 · 10^5 n/cm2 • s. The cost of the converter in this design is 585 thousand rubles, the weight of the installation is 4.8 tons, and the outer radius of housing is 1.2 m. Polyethylene was considered as a biological protection material and retardant in this version.

The best option of all using the Pu-Be source FNS-6 was the version in which the maximum density of thermal neutron flux in the working zone of the plant was achieved, equal to 800 n/cm^2·s. The cost of the converter in this design is 18 thousand rubles, the mass of the installation is 1 ton, and the outer radius of housing is 0.53 m. Water was considered as a biological protection material and retardant in this version (Fig. 6).

Among the variants using the Pu-Be source FNS-8, the best option was similar to the one discussed above for the source FNS-6 (Fig. 7).

Based on the results obtained, it is possible to optimize the design process of experimental plants of this type with various parameters, depending on the requirements set by the consumer.

As a result of the calculation for each version of the converter, the most advantageous characteristics were obtained: mass, cost, dimensions

For a potential customer, it is this output that will be boundary conditions, and it will be for them to choose the most suitable option. Each customer has a range of allowable values of each parameter, and having found options, all the parameters of which will lie in the corresponding ranges specified by the customer, it will be possible to offer him for consideration only those that satisfy all the requirements of the customer.

This technique allows you to find the most suitable options for each particular consumer as soon as possible, without wasting time calculating and selecting the necessary parameters, since all possible options have already been calculated.

To visualize and simplify this method, three-dimensional space was used, the ports of which are determined by three parameters set by the customer: the mass, dimensions and cost of the neutron converter. Each variant is shown as a point whose coordinates are determined by its corresponding parameters. Customer-defined ranges define a three-dimensional shape. If the point falls within the scope of this shape, then this means that the parameters of this option meet all the requirements of the customer (Fig. 10).

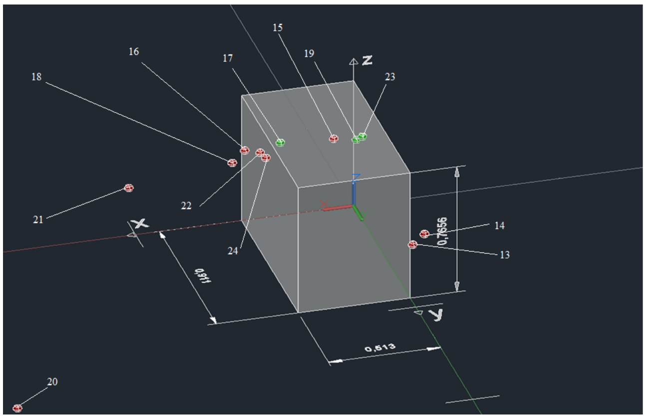

Fig. 10. An example of how to find the best option for a particular customer

For example, the customer's design requirements are as follows: it is necessary to design a neutron converter at the following specified parameters:

1. total cost: not more than 80 thousand rubles;
2. total weight: not more than 2 tons;
3. installation radius: not more than 0.58 m;
4. neutron source: FNS-6.

As shown in Fig. 8, the customer's stated requirements are met by options 17,19 and 23.

The highest density of thermal neutron flux in the working area of the plant: 800 n/cm^2·s is achieved in version 19. Therefore, it is advisable for the customer to propose a project with the characteristics of 19 version, in which concrete with water is used as the moderator materials, water as the biological protection (Table 1).

6. Conclusion

During the development of the method for optimizing the design procedure of the experimental neutron converter installation, the following results were obtained:

1. The regulatory documentation was analyzed.
2. A method for optimizing the neutron converter design procedure has been developed.
3. Based on the calculations made, a database of parameters of plant design implementation options was created, which became the basis of the method of optimizing the converter design procedure.
4. Analysis of the obtained calculation results was carried out, the most preferred materials for the plant design were identified, the most optimal design of the plant was determined.

Using the base of neutron converter design options and the method of optimizing the design procedure, it is possible to briefly present to potential customers optimal plant design options that meet all the requirements both from the consumer and from supervisory authorities.

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